

Optical Spectra and Light Curves of Supernovae

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Abstract. I review recent optical observations of supernovae (SNe) conducted by my group. The Lick Observatory Supernova Search with the 0.76-m Katzman Automatic Imaging Telescope is currently the world's most successful search for nearby SNe. We also use this telescope to obtain multicolor light curves of SNe. One of the more interesting SNe we discovered is SN 2000cx, which differs from all previously observed SNe Ia. Another very strange SN Ia that we studied is SN 2002cx, many of whose properties are opposite those of SN 2000cx. Extensive data on SNe II-P 1999em and 1999gi were used to derive distances with the expanding photosphere method. Results from spectropolarimetry suggest that the deeper we peer into the ejecta of core-collapse SNe, the greater the asphericity. We are using *Hubble Space Telescope* data to identify, or set limits on, the progenitors of core-collapse SNe.

1 The Lick Observatory Supernova Search (LOSS)

In 1989, my team began to work on developing a robotic telescope for CCD imaging of relatively faint objects. The history of the project is discussed in several papers (e.g., Filippenko *et al.* 2001; Richmond, Treffers, & Filippenko 1993), and several prototypes were used over the years. In 1996, we achieved first light with our present instrument, the 0.76-m Katzman Automatic Imaging Telescope (KAIT) at Lick Observatory on Mt. Hamilton, California. It took the better part of another year to eliminate most of the remaining bugs in the system, and useful scientific results started appearing in 1997. Absolutely vital contributions to the programming and to the observing strategy were made by Dr. Weidong Li, who joined my group in 1997.

KAIT is a fully robotic instrument whose control system checks the weather, opens the dome, points to the desired objects, acquires guide stars (in the case of long exposures), exposes, stores the data, and manipulates the data automatically, all without human intervention. We reach a limit of ~ 19 mag (4σ) in 25-s unfiltered, unguided exposures, while 5-min guided exposures yield $R \approx 20$ mag. KAIT acquires well-sampled, long-term light curves of SNe and other variable or ephemeral objects — projects that are difficult to conduct at other observatories having a large number of users with different interests.

One of our main goals is to discover nearby SNe to be used for a variety of studies. Special emphasis is placed on finding them well before maximum brightness. Although the original sample of our Lick Observatory Supernova Search (LOSS; Li *et al.* 2000; Filippenko *et al.* 2001) had only about 5000 galaxies, in

the year 2000 we increased the sample to $\sim 14,000$ galaxies (most with redshift $\lesssim 10,000 \text{ km s}^{-1}$), separated into three subsets (observing baselines of 2 days for about 100 galaxies, 3–6 days for ~ 3000 galaxies, and 7–14 days for $\sim 11,000$ galaxies). We are able to observe ~ 1000 galaxies per night in unfiltered mode. Our software automatically subtracts new images from old ones (after registering, scaling to account for clouds, convolving to match the point-spread-functions, etc.), and identifies SN candidates (Fig. 1) which are subsequently examined and reported to the Central Bureau for Astronomical Telegrams by numerous undergraduate research assistants in my group, working with Weidong.

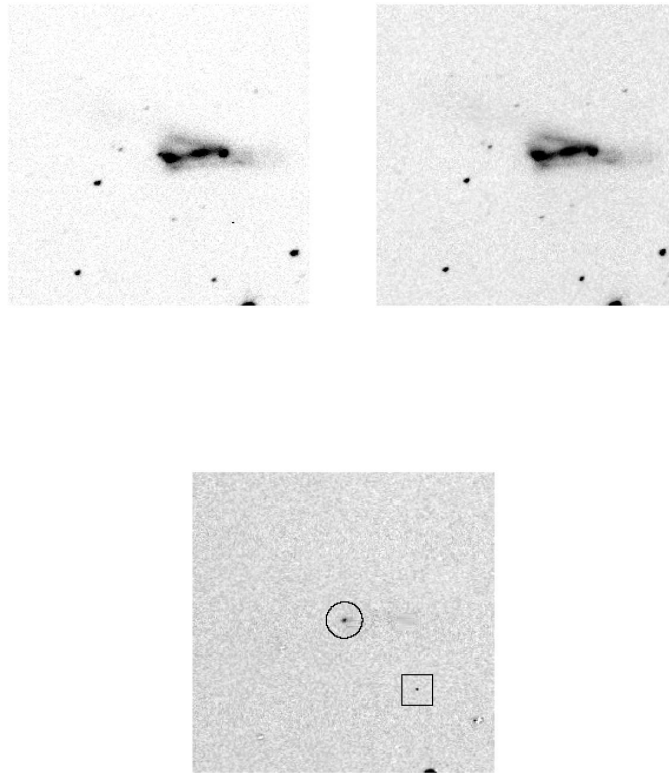


Fig. 1. KAIT images of NGC 523 before (*left*) and after (*center*) SN 2001en appeared. The difference image (*right*) shows the SN (circled), along with a cosmic ray (boxed).

A Web page describing LOSS is at <http://astro.berkeley.edu/~bait/kait.html>. LOSS found its first supernova in 1997 — SN 1997bs, which might not even be

a “genuine” SN (Van Dyk *et al.* 2000). In 1998, mostly during the second half of the year, LOSS discovered 20 SNe, thereby breaking the previous single-year record of 15 held by the Beijing Astronomical Observatory Supernova Search. In 1999, LOSS doubled this with 40 SNe. In 2000, LOSS found 38 SNe, even though we spent a significant fraction of the observing time expanding the database of monitored galaxies rather than searching for SNe. With this expanded database, LOSS discovered 68 SNe in 2001 and 52 SNe in 2002 through July. We discovered SN 2000A and SN 2001A, and hence the first supernova of the new millennium, regardless of one’s definition of the turn of the millennium! During the past few years, KAIT has discovered *about half* of all nearby SNe reported world-wide, from all searches combined — and through July 2002 it accounted for well over half (52/86) of them. Thus, KAIT/LOSS is currently the world’s most effective search engine for nearby SNe.

To further increase the sample of SNe, my group recently decided to coordinate with Michael Schwartz of the Tenagra Observatory (0.60 m and 0.75 m telescopes), using largely complementary sets of galaxies (the overlap between galaxy lists is larger during those months when either observatory often has bad weather). Our “Lick Observatory and Tenagra Observatory Supernova Search” (LOTOSS; Schwartz *et al.* 2000) should discover almost all of the nearby SNe over the accessible areas of the sky. Already, the Tenagra telescopes have discovered several SNe (e.g., Schwartz & Li 2001, 2002). Also, this strategy leaves KAIT with more time to conduct multicolor follow-up photometry of SNe.

At Lick and Keck Observatories, we spectroscopically confirm and classify nearly all of the SNe that other observers haven’t already classified. Thus, the sample suffers from fewer biases than most. The distribution of types through SN 2002dy is 93 SNe Ia, 76 SNe II, 12 SNe II_n, 1 SN II_b, 12 SNe Ib, 16 SNe Ic, and 6 unknown. We have started to determine the Hubble types of the host galaxies of the SNe (van den Bergh, Li, & Filippenko 2002), as a first step in the calculation of rates of various types of SNe. Already, our observations and Monte-Carlo simulations have shown that the rate of spectroscopically peculiar SNe Ia is considerably larger than had previously been thought (Li *et al.* 2001a).

Follow-up observations for the discovered SNe are emphasized during the course of LOSS. Our goal is to build up a multicolor database for nearby SNe. Because of the early discoveries of most LOSS SNe, our light curves usually have good coverage from pre-maximum brightening to post-maximum decline. Moreover, all LOSS SNe are automatically monitored in unfiltered mode as a byproduct of our search; these can sometimes be useful for other studies (e.g., Matheson *et al.* 2001). The positions of SNe in KAIT early-time images were used to identify the same SNe at very late times in *Hubble Space Telescope* images (Li *et al.* 2002), allowing us to determine the late-time decline rates.

LOSS also discovers novae in nearby galaxies (e.g., M31), cataclysmic variable stars, and occasionally comets (e.g., Li 1998). Although it records many asteroids, we don’t conduct follow-up observations, so most of them are lost.

2 SN 2000cx: A Very Weird SN Ia

High-quality observations of nearby SNe Ia provide valuable information about their progenitor evolution and the relevant physics. Analyses of samples of well-observed, nearby SNe Ia enable observers to study the differences among SNe Ia, empirical correlations, and possible environmental effects (e.g., Hamuy *et al.* 2000). It is thus important to expand the sample of well-observed nearby SNe Ia. Thus, a substantial fraction of KAIT’s time is devoted to follow-up photometry of bright SNe Ia.

Moreover, studies of high-redshift SNe Ia have revealed a surprising cosmological result, that the expansion of the Universe is currently accelerating, perhaps due to a nonzero cosmological constant (e.g., Riess *et al.* 1998, 2001; Perlmutter *et al.* 1999). This result, however, is based on the assumption that there are no significant differences between SNe Ia at high redshift and their low-redshift counterparts. In particular, we rely on the luminosity/light-curve correlation, as quantified in a number of ways (e.g., Riess *et al.* 1998); Phillips *et al.* 1999; Perlmutter *et al.* 1999), to “standardize” the luminosities of different SNe Ia. But what if some SNe Ia don’t conform with this correlation? If there are more of them at high redshifts than at low redshifts, systematic errors may creep into the analysis. We need to find and investigate such objects at low redshifts.

SN 2000cx in the S0 galaxy NGC 524 is a case in point. It was discovered and confirmed by LOSS in July 2000, and it became the brightest SN of the year 2000. A follow-up program of multicolor photometry and spectroscopy was established at Lick Observatory; photometry of SN 2000cx was also gathered at the Wise Observatory in Israel. The results are described in detail by Li *et al.* (2001b); here I summarize the main points.

A very peculiar object, SN 200cx is, indeed, unique among all known SNe Ia. The light curves cannot be fit well by any of the fitting techniques currently available (e.g., MLCS and the stretch method); see Figure 2. There is an apparent asymmetry in the rising and declining parts of the *B*-band light curve, while there is a unique “shoulder”-like evolution in the *V*-band light curve. The *R*-band and *I*-band light curves have relatively weak second maxima. In all *BVRI* passbands the late-time decline rates are relatively large compared to other SNe Ia.

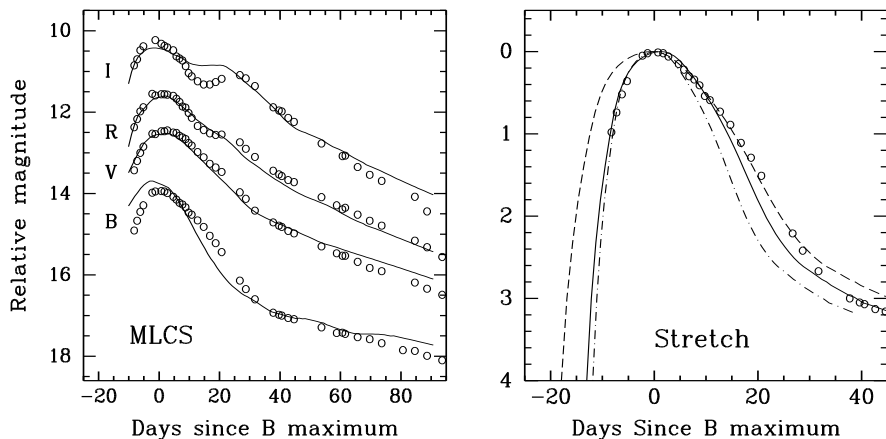


Fig. 2. The MLCS fit (Riess *et al.* 1998; *left panel*) and the stretch method fit (Perlmutter *et al.* 1999; *right panel*) for SN 2000cx. The MLCS fit is the worst we had ever seen through 2000. For the stretch method fit, the solid line is the fit to all the data points from $t = -8$ to 32 days, the dash-dotted line uses only the premaximum datapoints, and the dashed line only the postmaximum datapoints. The three fits give very different stretch factors. From Li *et al.* (2001b).

SN 2000cx has the reddest $(B - V)_0$ color before $t \approx 7$ days among several SNe Ia, and it subsequently has a peculiar plateau phase where $(B - V)_0$ remains at 0.3 mag until $t = 15$ days. The late-time $(B - V)_0$ evolution of SN 2000cx is found to be rather blue, and is inconsistent with the fit proposed by Lira (1995) and Phillips *et al.* (1999). SN 2000cx also has very blue $(V - R)_0$ and $(V - I)_0$ colors compared with other SNe Ia.

Our earliest spectrum of SN 2000cx ($t = -3$ days) reveals remarkable resemblance to those of SN 1991T-like objects, with prominent Fe III lines and weak Si II lines. As in the case of SN 1991T, Si II lines strengthened around the time of maximum brightness. However, the subsequent spectral evolution of SN 2000cx is quite different from that of SN 1991T. The Fe III and Si II lines remain strong, and the Fe II lines remain weak, in the spectra of SN 2000cx until $t \approx 20$ days, indicating that the excitation stages of iron-peak elements change relatively slowly in SN 2000cx compared with other SNe Ia, and suggesting that the photosphere of SN 2000cx stays hot for a long time. Both iron-peak and intermediate-mass elements are found to be moving at very high velocities in SN 2000cx. The V_{exp} measured from the Si II $\lambda 6355$ line shows a peculiar (nearly constant) evolution.

We find that the delayed detonation model DD3 (Woosley & Weaver 1994) investigated by Pinto & Eastman (2001) accounts for the observations of SN 2000cx rather well. This model suggests that SN 2000cx is similar to SN 1991T, but with a larger ^{56}Ni production and a higher kinetic energy (i.e., greater expansion velocity for the ejecta). We emphasize that because of uncertainties in the current theoretical models for SNe Ia, various views should be considered.

For example, the big difference between SN 2000cx and SN 1991T in their V , R , and I light curves may suggest that they are two very different objects.

3 SN 2002cx: An Even Weirder SN Ia

But SN 2000cx is not the end of the story, when it comes to peculiar SNe Ia. A more recent, even stranger SN Ia was SN 2002cx, many of whose properties are the opposite of those of SN 2000cx! SN 2002cx was discovered in May 2002 by Wood-Vasey *et al.* (2002) with the Oschin 1.2-m telescope at Palomar Observatory in unfiltered images. Its host galaxy is CGCG 044-035, at a redshift of $cz = 7184 \text{ km s}^{-1}$ (determined from H II region emission lines). An optical spectrum (Matheson *et al.* 2002) identified the SN as a peculiar SN 1991T-like event at about a week before maximum brightness, but the object is very *underluminous* (instead of somewhat overluminous) compared with normal SNe Ia. The Si II $\lambda 6355$ and Ca II H & K lines are extremely weak or absent, but the Fe III lines at 4300 \AA and 5000 \AA are present and indicate very low expansion velocity — only half that of normal SNe Ia.

Recognizing the uniqueness of SN 2002cx shortly after its discovery, we established a follow-up program of multicolor photometry at Lick Observatory. Spectra of the SN were obtained with the Fred L. Whipple Observatory 1.5-m telescope and also with the Keck 10-m telescopes. Li *et al.* (2003) discuss the results in detail; here I provide only a brief summary.

Besides being subluminous by $\sim 2 \text{ mag}$ at all optical wavelengths relative to normal SNe Ia (implying that only a small amount of ^{56}Ni was produced), SN 2002cx has peculiar photometric evolution (Fig. 3). In the B band it has a decline rate of $\Delta m_{15}(B) = 1.29 \pm 0.11 \text{ mag}$, similar to those of SN 1994D and SN 1999ac, but it is less luminous by $\sim 1.4 \text{ mag}$ than SN 1994D and SN 1999ac. The R band has a broad peak, and the I band has a unique plateau that lasts until about 20 days after B maximum. The late-time decline is rather slow in all BVR bands. The $(B - V)$ color evolution is nearly normal, but the $(V - R)$ and $(V - I)$ colors are very red.

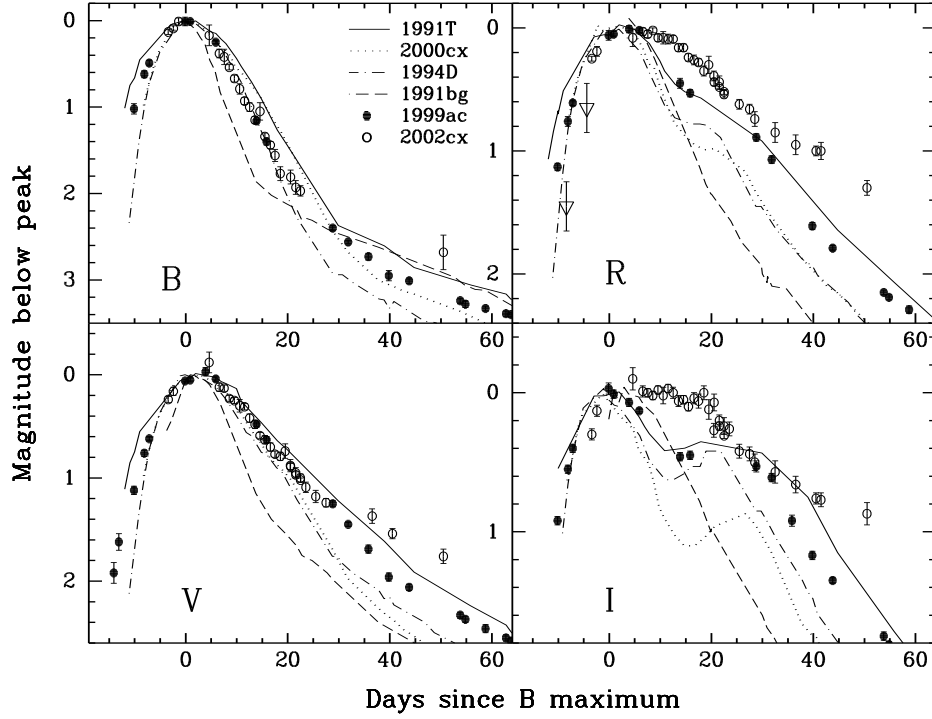


Fig. 3. Comparison (Li *et al.* 2003) between the *B*, *V*, *R*, *I* light curves of SN 2002cx and those of SN 1991T (Lira *et al.* 1998), SN 2000cx (Li *et al.* 2001b), SN 1994D (Richmond *et al.* 1995), SN 1991bg (Filippenko *et al.* 1992; Leibundgut *et al.* 1993), and SN 1999ac (Li *et al.*, in preparation). All light curves are shifted in time and peak magnitude to match those of SN 2002cx.

The premaximum spectrum of SN 2002cx resembles those of SN 1991T-like objects, but with extremely low expansion velocities, the lowest ever measured for a SN Ia. The spectral evolution is dominated by Fe-group element lines, with very weak intermediate-mass element features. The nebular phase was reached unprecedently soon after maximum, despite the low velocity of the ejecta, implying that the ejected mass is low. The nebular-phase spectrum is also quite different from those of other SNe Ia (Fig. 4); there are mysterious emission lines near 7000 Å around 3 weeks after maximum brightness, and other differences as well. At late times, the spectrum is dominated by very narrow Fe II and Co II lines, and the object is very red.

SN 2002cx is inconsistent with the observed SN Ia decline rate vs. luminosity relation, or the spectral vs. photometric sequence. No existing theoretical model

successfully explains all observed aspects of SN 2002cx, though the pulsating delayed detonation of a Chandrasekhar-mass white dwarf or the He detonation of a sub-Chandra white dwarf have some promising characteristics and should be pursued further.

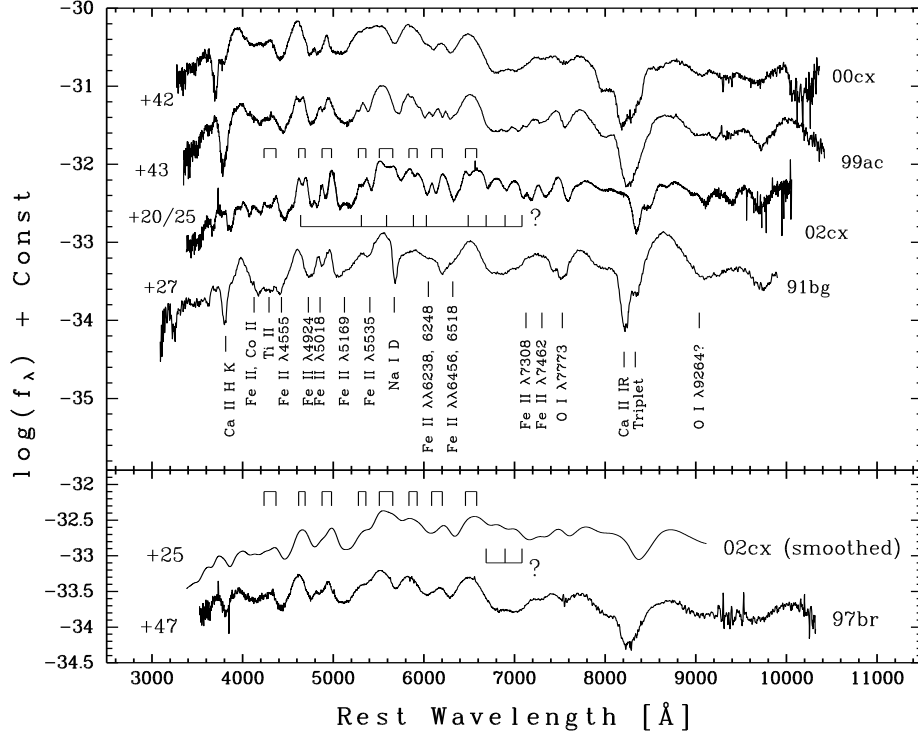


Fig. 4. The spectrum of SN 2002cx at $t = +20/25$ d, shown with spectra of other SNe Ia at older ages (Li *et al.* 2003). The *upper panel* shows the line identifications and the comparison of the spectra. The pairs of short vertical lines above the SN 2002cx spectrum mark possible “double peaks,” while these below the SN 2002cx spectrum mark possible additional resolved lines (compared with other SNe Ia). The lower panel shows the comparison between the $t = +25$ d spectrum of SN 2002cx after convolving with a Gaussian function with $\sigma = 2,500$ km s $^{-1}$, and the day +47 spectrum of SN 1997br. Note that although the “double peaks” are gone, additional features seem to be present around 7000 Å in the spectrum of SN 2002cx.

4 Studies of Type II Supernovae

We have also used KAIT to obtain excellent light curves of SNe II, with complementary spectra obtained at Lick Observatory and elsewhere. These are being used to study the physical properties of SNe II, and also to derive distances

through the expanding photosphere method (EPM), a variant of the Baade (1926) method used to measure distances to variable stars.

In two detailed studies, we derived EPM distances to SN 1999em ($D = 8.2 \pm 0.6$ Mpc; Leonard *et al.* 2002a) and SN 1999gi ($D = 11.1^{+2.0}_{-1.8}$; Leonard *et al.* 2002b). In addition to its cosmological use, knowing the EPM distance to SN 1999gi allowed us to set constraints on the upper mass limit of its progenitor star of $15^{+5}_{-3} M_{\odot}$, through the analysis of predisccovery images. This is substantially less restrictive than the upper mass limit ($9^{+3}_{-2} M_{\odot}$) recently found in the same manner by Smartt *et al.* (2001, 2002). The increased upper limit results mainly from the larger distance derived through EPM than was assumed by the Smartt *et al.* (2001, 2002) analyses, which relied on less precise (and less recent) distance measurements to NGC 3184.

We have also obtained high signal-to-noise ratio spectropolarimetry of some SNe II-P with the Keck 10-m and Lick 3-m telescopes (Leonard *et al.* 2001). At early times, SNe II-P appear to be polarized very little, suggesting that any departures from spherical symmetry are small. This is encouraging news for those who attempt to derive EPM distances for SNe II-P: Unlike the empirically based method used to measure distances to SNe Ia, distances derived to SNe II-P rely on the assumption of a spherically symmetric flux distribution during the early stages of development (i.e., the plateau). We plan to obtain spectropolarimetry of additional SNe II-P, in order to much more thoroughly test the fundamental assumption of spherical symmetry in EPM.

However, multi-epoch spectropolarimetry shows that the polarization increased with time (Fig. 5a), implying a substantially spherical geometry at early times that becomes more aspherical at late times when the deepest layers of the ejecta are revealed. In addition, our data on other core-collapse SNe indicates large polarizations for objects that have lost much of their envelope prior to exploding (e.g., SN Ic 2002ap, Fig. 5b; see below, and Leonard *et al.* 2002c). For core-collapse events, then, it seems that the closer we probe to the heart of the explosion, the greater the polarization and, hence, the asymmetry. The current speculation is that the presence of a thick hydrogen envelope dampens the observed asymmetry.

5 The Peculiar SN Ic 2002ap

Although core-collapse SNe present a wide range of spectral and photometric properties, there is growing consensus that much of this variety is due to the state of the progenitor star's hydrogen and helium envelopes at the time of explosion. Those stars with massive, intact envelopes produce Type II-plateau SNe, those that have lost their entire hydrogen envelope (perhaps through stellar winds or mass transfer to a companion) result in SNe Ib, and those that have been stripped of both hydrogen and most (or all) of their helium produce SNe Ic; see Filippenko (1997) for a general review.

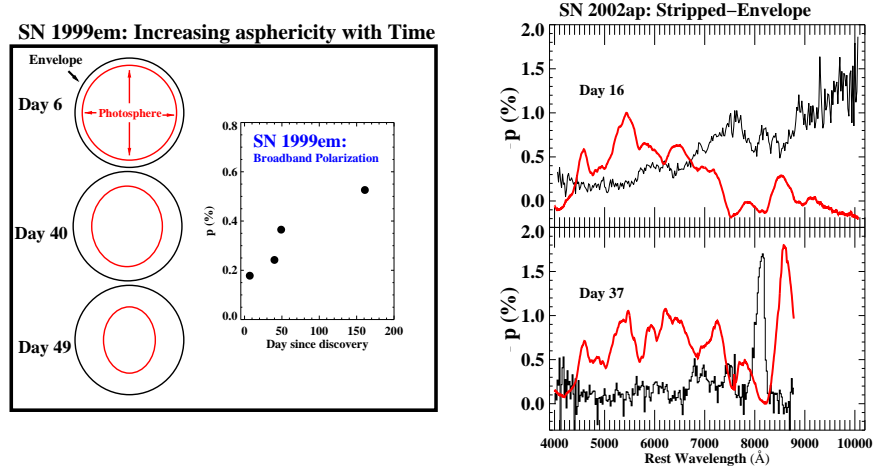


Fig. 5. (a) (*left*) The temporal increase in the polarization of the Type II-P SN 1999em suggests greater asphericity deeper into the ejecta. (b) (*right*) Polarization level (*thin noisy lines*) of the peculiar SN Ic 2002ap, with relative flux (*thick smooth lines*) overplotted for comparison of features (Leonard *et al.* 2002c).

Recently, a new subclass of objects has emerged whose members generically resemble SNe Ic (no hydrogen or obvious helium spectral features), but, unlike traditional SNe Ic, have spectra characterized by unusually broad features at early times, indicating velocities in excess of $\sim 30,000 \text{ km s}^{-1}$. A few also possess inferred kinetic energies exceeding that of “normal” core-collapse SNe by more than a factor of 10 (see, e.g., Nomoto *et al.* 2001). These objects are colloquially referred to as “hypernovae,” although not all of them are clearly more luminous or energetic than normal SNe Ic.

Intense interest in hypernovae has been sparked not only by their peculiar spectral features, but also by the strong spatial and temporal association between the brightest and most energetic of these events, SN 1998bw, and the γ -ray burst (GRB) 980425 (e.g., Galama *et al.* 1998). There are only a few generally accepted members of this rare class (e.g., SN 1997dq, SN 1997ef). A related subclass of SNe exhibits many of the characteristics of these objects, but with hydrogen present in the spectra; the clearest examples are SN 1997cy and SN 1999E (Germany *et al.* 2000; Turatto *et al.* 2000; Filippenko 2000, and references therein), and they, too, are sometimes called hypernovae. The hydrogen emission probably comes from the interaction of relatively hydrogen-poor ejecta with circumstellar gas previously expelled by the progenitor star (and richer in hydrogen than the remaining parts of the progenitor).

SN 2002ap in M74 (Mazzali *et al.* 2002) is one of the most recent examples of a peculiar SN Ic of this kind. So far, it has been the brightest supernova of the year 2002. Though not discovered by LOSS (it went off between two KAIT observations, but was discovered during that interval by Yoji Hirose [IAUC 7810]), KAIT’s observations set a useful limit on the explosion date.

Figure 6 shows the spectrum of SN 2002ap obtained after the SN reappeared following solar conjunction, about 5 months after maximum brightness. It is characterized by strong emission lines of intermediate-mass elements superimposed on a weak continuum, implying that the SN has entered the nebular phase. Unusual narrow lines are visible on top of some of the broad-line profiles, including especially those of [O I] $\lambda\lambda 6300, 6364$ and Mg I $\lambda 4571$.

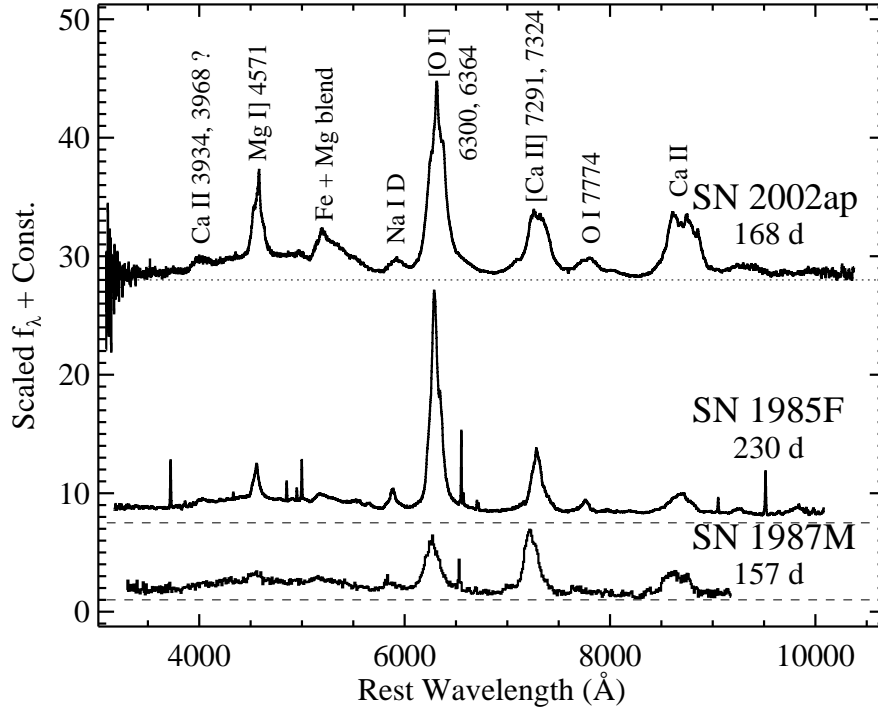


Fig. 6. SN 2002ap (*top*) in the nebular phase, compared with the SN Ib/Ic 1985F (*middle*) and the “ordinary” Type Ic SN 1987M (*bottom*) at similar epochs; the estimated day since explosion is indicated. The exact spectral classification of SN 1985F is unknown, since it was discovered long after maximum brightness (see Filippenko & Sargent 1986; Filippenko 1997), but it provides the closest match we could find to the spectrum of SN 2002ap. The spectra are scaled so that the height of the [Ca II] $\lambda\lambda 7319, 7324$ blend is approximately the same in all three cases.

Although there is no guarantee that the three objects were at the same stage of their development (they may evolve at different physical rates, even if they are approximately the same calendar age), one can see in Figure 6 that relative to SN 1987M, a typical SN Ic, SN 2002ap has *much* stronger [O I] and Mg I emission. The only SN Ib/Ic we have found comparable to SN 2002ap is SN 1985F, as shown. However, SN 2002ap exhibits a larger Mg I $\lambda 4571$ to [O I] $\lambda\lambda 6300, 6364$

ratio than that of SN 1985F, suggesting that we are seeing even closer to the O-Ne-Mg layer in SN 2002ap. Qualitatively, this supports the hypothesis that SN 2002ap (and perhaps other peculiar examples of the SN Ic subclass) have progenitors that are even more highly stripped than normal SNe Ic. There might be other factors to consider as well, but the sequence II-P \rightarrow IIb \rightarrow Ib \rightarrow Ib/c \rightarrow Ic \rightarrow Ic-pec may fundamentally be one dominated by the degree to which the envelope of the progenitor has been stripped.

6 The Progenitors of Core-Collapse SNe

Identifying the massive progenitor stars that give rise to core-collapse SNe is one of the main pursuits of supernova and stellar evolution studies. Using ground-based images of recent, nearby SNe obtained primarily with KAIT, astrometry from the Two Micron All Sky Survey, and archival images from the *Hubble Space Telescope*, we have attempted the direct identification of the progenitors of 16 Type II and Type Ib/c SNe (Van Dyk *et al.* 2002).

We may have identified the progenitors of the Type II SNe 1999br in NGC 4900, 1999ev in NGC 4274, and 2001du in NGC 1365 as supergiant stars with $M_V^0 \approx -6$ mag in all three cases. We may have also identified the progenitors of the Type Ib SNe 2001B in IC 391 and 2001is in NGC 1961 as very luminous supergiants with $M_V^0 \approx -8$ to -9 mag, and possibly the progenitor of the Type Ic SN 1999bu in NGC 3786 as a supergiant with $M_V^0 \approx -7.5$ mag.

Additionally, we have recovered at late times SNe 1999dn in NGC 7714, 2000C in NGC 2415, and 2000ew in NGC 3810, although none of these had detectable progenitors on pre-supernova images. In fact, for the remaining SNe only limits can be placed on the absolute magnitude and color (when available) of the progenitor. The detected Type II progenitors and limits are consistent with red supergiants as progenitor stars, although possibly not as red as we had expected. Our results for the SNe Ib/c do not strongly constrain either Wolf-Rayet stars or massive interacting binary systems as progenitors.

7 Acknowledgments

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